

22. NORDENSKJÖLD, OTTO, and MECKING, LUDWIG.
The Geography of the Polar Regions. American Geographical Society, Special Publication No. 8. New York, published by the society, 1928. 359 p.
23. STEFANSSON, VILHELMAR.
The Friendly Arctic. New York, Macmillan & Co., 1921. 784 p.
24. STUCK, HUDSON.
Voyages on the Yukon and its Tributaries. New York, Charles Scribner's Sons, 1917. 397 p.
25. ———.
A Winter Circuit of our Arctic Coast. New York, Charles Scribner's Sons, 1920. 347 p.
26. STUPART, SIR FREDERIC.
The Influence of Arctic Meteorology on the Climate of Canada Especially. Pp. 39-50, in Problems of Polar Research, a series of papers, American Geographical Society, Special Publication No. 7. New York, published by the society, 1928. 479 p.
27. STUPART, SIR FREDERIC, PATTERSON, J., and SMITH, H. GRAYSON.
Ocean Surface-Water Temperatures: Methods of Measuring and Preliminary Results. Pp. 76-88, in Bulletin of the National Research Council, No. 68, published by the National Research Council, Washington, 1929.
28. SUMMERS, MELVIN B.
Some Features of the Climate of Alaska. Pp. 493-496, in MONTHLY WEATHER REVIEW, vol. 52, no. 10, 1924.
29. ———.
Summary of the Climatological Data for Alaska. 3 sections. Climatological data herein from the establishment of the stations to 1921 inclusive. U. S. D. A., Weather Bureau, Washington, 1925. Each section about 18 p.
30. TRANSEHE, N. A.
The Ice Cover in the Arctic Sea, with a Genetic Classification of Sea Ice. Pp. 91-123, in Problems of Polar Research, a series of papers, American Geographical Society, Special Publication No. 7. New York, published by the society, 1928. 479 p.
31. UNDERWOOD, JOHN J.
Alaska, An Empire in the Making. Rev. ed., New York, Dodd, Mead & Co., 1925. 440 p.
32. U. S. DEPARTMENT OF AGRICULTURE.
Atlas of American Agriculture. Part II, Section B, Temperature, Sunshine, and Wind. Washington, Government Printing Office, 1928. 34 p.
33. U. S. DEPARTMENT OF AGRICULTURE.
Possible Agricultural Development in Alaska. Department Bulletin No. 50. Washington, Government Printing Office, 1914. 31 p.
34. U. S. DEPARTMENT OF COMMERCE AND LABOR.
Commercial Alaska, 1867-1903. Washington, Government Printing Office, 1904.
35. U. S. NAVY DEPARTMENT, HYDROGRAPHIC OFFICE.
Pilot Charts of the North Pacific Waters. Issued monthly. Washington, D. C.
36. U. S. WEATHER BUREAU.
Annual Report of the Chief. Washington, Government Printing Office, 1917.
37. U. S. WEATHER BUREAU.
Climatological data. Alaska Section. Weather Bureau Office, Juneau, Alaska, 1917. Annual summaries, 1917-1926. Monthly summaries, 1917-July 1927.
38. U. S. WEATHER BUREAU.
Climatological Data for Alaska. Manuscript tables from the U. S. Weather Bureau, 1927.
39. U. S. WEATHER BUREAU.
Extensions of U. S. Weather Bureau Service. p. 463, in Monthly Weather Review, vol. 44, 1916.
40. WARD, ROBERT DECOURCY E.
Climate, Considered Especially in Relation to Man. New York, G. P. Putnam's Sons. Rev. ed. 1918. 380 p.
41. ———.
The Climates of the United States. Boston, Ginn & Co., 1925. 518 p.
42. WILKINS, CAPT. SIR HUBERT.
The Flight from Alaska to Spitzbergen, 1928, and the Preliminary Flights of 1926 and 1927. pp. 527-555, in the Geographical Review, vol. XVIII, October 1928.
43. WORLD WEATHER REPORTS.
Arranged for publication by H. Helm Clayton. Smithsonian Miscellaneous Collections, vol. 79, published by the Smithsonian Institution, Washington, 1927. 1199 p.
44. AHLMANN, H. W.
Karta över den Årliga Nederbördens Fördelning på Skandinaviska Halvön. Un resumé en français. Stockholm, 1925. 8 p.
45. HANN, JULIUS.
Handbuch der Klimatologie. Stuttgart, Verlag von J. Engelhorn's Nachf., 1911. 3 vol. Vol. III, pp. 647-653, on Alaska. References cited.
46. NORSKE METEOROLOGISKE INSTITUT.
Nedbøriakttagelser I Norge. Published annually at Oslo. ca. 85 p.

GULF STREAM STUDIES: GENERAL METEOROLOGICAL PROJECT

By CHARLES F. BROOKS

[Clark University, Worcester, Mass., March 15, 1930]

THE GULF STREAM AND THE WEATHER

It is the common impression along the Atlantic seaboard that the Gulf Stream has important effects on the weather. When the wind blows on-shore from an easterly to southerly direction for some time, balmy air, of soft springlike quality, usually reaches the shores. A number of such occurrences in a season suggest that the Gulf Stream is nearer or warmer than usual.

But there is another side to the matter. Winds are prevailingly offshore in the colder months, so the character of these land winds will dominate the season. Winds from the west or northwest are generally cool and dry on the Atlantic slope, and the stronger they are the more pronounced are these characteristics. More northerly winds now and then attend much snowfall.

Now, how can the Gulf Stream have anything to do with these winds blowing toward it? Through storms, is the answer. We know that, whatever the wind direction and velocity, they are in accordance with the particular distribution of pressure at the time. To provide a maximum of westerly to northerly winds, therefore, we should have a frequent occurrence of low-pressure areas

centered off the coast (1). And this will occur most readily when conditions most favor storms there. It is generally agreed that the sources of energy for oceanic storms are abundant heat energy latent in water vapor and marked contrasts in temperature. The Gulf Stream supplies much water vapor and its warmth is in great contrast to the coolness of the neighboring continent. Therefore, the Gulf Stream favors the very winds and snows that make our eastern climates cooler than the averages for their latitudes.

THE GULF STREAM

High temperature, speed, magnitude, and location make the Gulf Stream the best known of all ocean currents. The habitability of northwestern Europe is commonly ascribed to the high temperatures of the Gulf Stream, though this current is only part of the warm flow that ameliorates European climate (2). The climatic importance of the Gulf Stream and the other warm waters of the western Atlantic has still to be fully appreciated. It is generally recognized, however, that these warm seas are the sources of rainfall for eastern North America and the progenitors of storms.

The speed of the current, 1 to 4 knots, is a notable aid or hindrance to navigation, though less so nowadays than in the period of sailing ships. The commerce of the busiest ocean feels the movement, the warmth, and the storms of the Gulf Stream. Even aerial navigation is disturbed by the bumpy air over it. The clear blue waters of this tropical current are sharply contrasted with the colder green waters on its left, while the Gulf Weed (Sargassum) and tropical fauna, including the picturesque Portuguese man-of-war (*Physalia spec.*), add their touch of life.

The breadth of the Stream and its unseen depth make even the mightiest rivers seem tiny. A ship steaming across even its narrowest section, in the Straits of Florida, where the Gulf Stream occupies practically the entire width of the Straits, loses sight of land long before the

becomes entangled with the Labrador Current (6). (See map, fig. 2.) Beyond the Grand Banks the contrasts are so diminished that the current is considerably slower. The surface waters drift generally eastward before the prevailing westerly winds (7). This is the Gulf Stream in brief, a much talked about but still relatively little studied river in the sea.

The United States Coast and Geodetic Survey, beginning in Maury's time, has sent many expeditions to study the Gulf Stream, the results up to 1890 being presented by John E. Pillsbury in an extensive appendix (No. 10) to the United States Coast and Geodetic Survey report for 1890 (8). Nor did its work stop here; its investigations have continued from time to time till the present, some of the latest ocean data having been gathered on the *S. S. Lydonia* early in 1929. The United States Bureau of

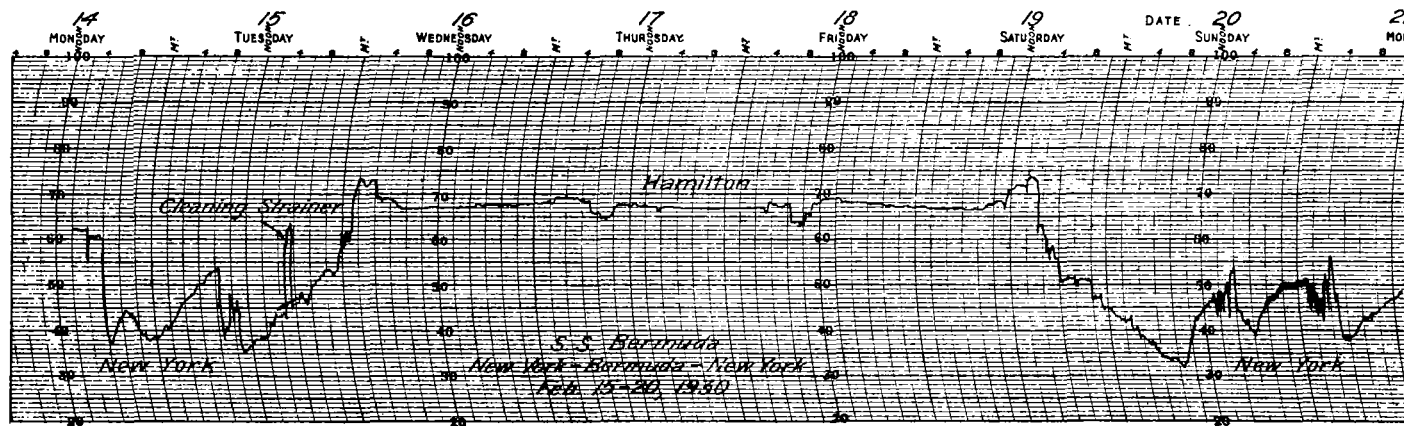


FIGURE 1.—Profile of sea temperature between New York and Bermuda February 15-20, 1930, made by sea-water thermograph on motor ship *Bermuda* of the Furness-Bermuda Line

There was a notable rise of sea temperature from 35° at New York to 53° at the north side of the cold wall, and then jumped upward 8°, then 12°, to 73° as the Gulf Stream was entered. The really warm portion of the Gulf Stream was soon passed, and the Stream was left altogether about five hours after it was entered. The temperature of the Antilles Current between it and Bermuda ranged from 67° to 68°. On the return trip the Antilles Current was slightly cooler, the maximum temperature of the Gulf Stream, however, slightly higher, nearly 74°. Also, the fall at the cold wall was greater, amounting to 22°. The total fall from the warmest of the Gulf Stream to the coldest at New York, 32.5°, was over 41°.

On the outbound trip there was a northwesterly to northerly gale with snow. At 2 and 4 a. m. the 16th, while the thermograph recorded 73°, the bucket observations showed but 59° and 65°, so great was the cooling by the cold gale. There could be no clearer demonstration of the difficulty of obtaining satisfactory sea temperature records with a canvas bucket in severe weather.

The ship left New York (Fairway buoy, off Ambrose Lightvessel) at 12:52 p. m., February 15th, was at 35° 49' N., 68° 32' W., at noon the 16th, and arrived at Bermuda (Mills breaker buoy) at 7:11 a. m. the 17th. Returning, it left Bermuda at 10 a. m. February 18th, was at 37° 00' N., 70° 07' W., at noon February 19th, and arrived in New York 5:33 a. m. the 20th. The ship's speed on this voyage was about 16 knots. The tidal ups and downs of temperature before noon on the 15th and after 9 a. m. the 20th are temperature changes while the ship was at dock.

This record was obtained through the courtesy of Mr. Benjamin Parry, in charge of the marine work, New York office, United States Weather Bureau.

[Since this map was prepared, it has been learned that one of the Canadian ships covers the route from Bermuda to Trinidad, thus providing a temperature record all the way across the Equatorial Current as it enters the Caribbean Sea.—Author.]

other shore appears. The crossing is a matter of hours, and the sideways drifting of the vessel in the current, a distance reckoned in miles, sometimes tens of miles. In the Straits the current extends to maximum depths of half a mile to a mile.

The general flow arises from the difference in level between the warmed and expanded tropical waters and the denser colder waters of higher latitudes (3), while the particular concentration of the current into a fairly swift river 40 to 60 miles wide and half a mile to a mile or more deep is due largely to the trade winds and the configuration of the West Indies and eastern coast of North America. After leaving the confining Straits of Florida the Gulf Stream spreads, becoming less deep and prominently streaked with cooler bands. It maintains, however, a "cold wall" on its left. (See fig. 1.) The greater density of the much colder waters causes lower pressures level for level west and north of this cold wall than those of the warm Gulf Stream, which is clearly to be seen on Jacobsen's topographic maps, for the surface, 200, 500, and 800 meters depth (4). This pressure gradient and the deflective effect of the earth's rotation continue to drive the waters rapidly (5), northeastward then eastward to the Grand Banks, where the Gulf Stream

Fisheries has also been prominent in Gulf Stream studies (9). Some recent observations have been made by P. Idrac on the yacht *Jamaica* (10). Present knowledge of this great ocean current is admirably summarized from the physical oceanographic standpoint, by H. A. Marmer, of the United States Coast and Geodetic Survey, in a recent paper in the *Geographical Review* (11), and by Georg Wüst, general secretary, *gesellschaft für Erdkunde*, Berlin (12). From a meteorological angle, general statements by C. F. Brooks, and H. V. Miller appeared last year in the *Bulletin of the American Meteorological Society* (13), and by C. F. Brooks in the *MONTHLY WEATHER REVIEW* in 1918 (14). All these papers contain references to earlier ones.

THE GENERAL METEOROLOGICAL PROJECT FOR INVESTIGATING THE GULF STREAM

In the paper on "Ocean Temperatures in Long-Range Forecasting" (14), 11 years ago, the writer indicated: (1) How the Gulf Stream as a warm body of water favored precipitation, storminess, and low pressure, thereby constituting an important factor in the climate of our eastern seaboard—in winter, for example, favoring

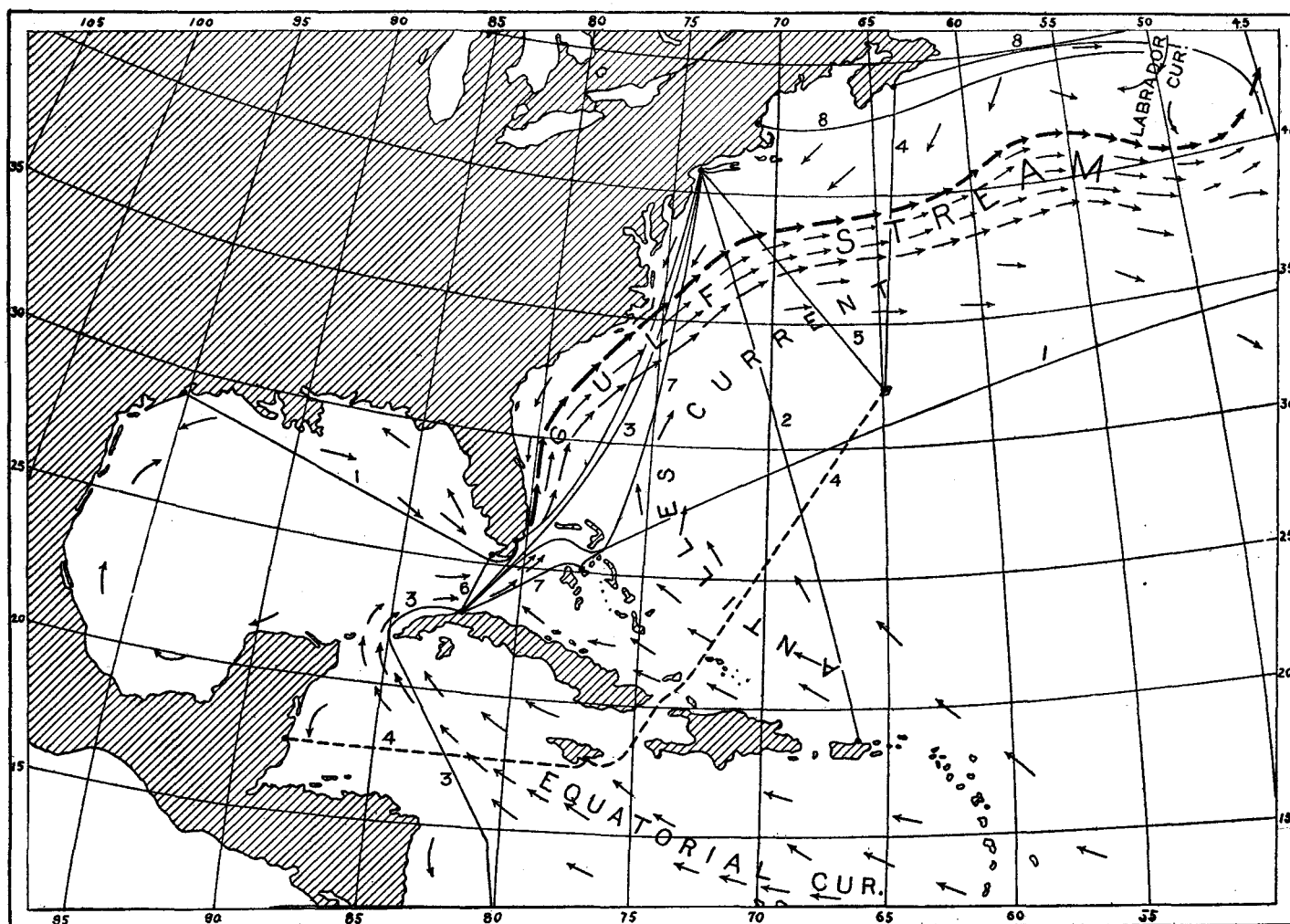


FIGURE 2.—The Gulf Stream (after Pillsbury (7), Smith (5), and United States Hydrographic Office, North Atlantic Pilot Chart, March, 1924, and steamship lines on which one or more sea-water thermographs are regularly crossing it): (1) French training ship *Jacques Cartier*, Le Havre to Gulf ports, with the first sea-water thermograph regularly crossing the Gulf Stream; (2) the Porto Rican Line steamship *Coamo*, instrument purchased by United States Weather Bureau (1926); (3) the Panama Pacific Line steamships *California*, *Virginia*, and (later) *Pennsylvania*, instruments purchased by Clark University (1926), the American Meteorological Society (1930) and (later) the Panama Pacific Line (1930); (4) on steamships *Canadian Forester* and *Canadian Fisher*, Montreal or Halifax to British Honduras, instruments purchased by Canadian Meteorological Service (1927); (5) the Furness-Bermuda Line motorship *Bermuda*, thermograph purchased by the Furness-Bermuda Line (1928); (6) Peninsular and Occidental steamship *Henry M. Flagler*, between Key West and Habana, instrument purchased by the American Meteorological Society (1928); (7) The Munson Line (7) is purchasing a sea-water thermograph for steamship *Munargo*, on the route New York-Nassau-Habana-Miami-New York. The International Ice Patrol (8), operating from Boston and Halifax to the Grand Banks during the iceberg season, February or March to July, installed sea-water thermographs on its two ships, the *Mojave* and the *Modoc*, in 1927. That on the *Modoc*, however, was transferred to the *Marion*, in 1928, and later was destroyed by fire. The instrument on the *Mojave* is being removed temporarily for repairs. All these instruments are under the general charge of the French, Canadian, or United States Governments, the seven out of New York being under the care of Mr. Benjamin Parry, marine official, New York office, United States Weather Bureau. The records from the Canadian ships go to Dr. A. G. Huntsman, of Toronto University; those from the Panama Pacific liners and the Peninsular and Occidental Line to the writer; and the rest to the United States Weather Bureau, Washington. Photostat copies of thermograms from the *Jacques Cartier* are filed in the Hydrographic Office, U. S. Navy, Washington.

colder and wetter weather than if the waters were not so warm; (2) how variations in Gulf Stream temperatures from year to year, even though amounting to no more than 2° or 3° F. on either side of the normal, are probably in part responsible for considerable seasonal variations in the character of our eastern seasons, and (3) how through movements of temperature departures in the Gulf Stream it should be possible to anticipate some of our seasonal weather abnormalities.

The then available data on Gulf Stream temperatures, obtained by inserting thermometers in samples of sea water drawn up from the surface in a small canvas bucket, proved to have inaccuracies considerably greater than the variations to be studied. An average error of 5° F. was found in the bucket data obtained on a number of steamships crossing the Gulf Stream in the open Atlantic in winter (15). The Gulf Stream is warmer than our past records have given it credit for being. The inaccuracies of the old method led to the now considerable installation of sea-water thermographs, which give both accurate and continuous records on several lines across the Gulf Stream. (Fig. 2.)

The surface temperature of the Gulf Stream averages 80° F. in the Straits of Florida, ranging from 73 to 77 in February or March to 85 or 86 in August in the left and right portions of the Stream at the western entrance to the Straits. Though the thermograph data for other portions of the Gulf Stream have not yet been reduced, an inspection of the records indicates that the temperatures of the Gulf Stream fall but slowly downstream to the northeast. This is owing to the speed of the stream and to the great mass of water involved, even though such a high temperature does not extend far below the surface. Pillsbury (8) and others (12) have estimated that the flow of water is about 90 billion tons an hour, roughly half of which is the warm upper 200 meters. Southeast of New York the Gulf Stream does not fall below 70° in its warmest portion at any time of the year, while in summer its temperature exceeds 80° . Near the Grand Banks the temperatures are 5° to 10° lower, though still so much above the coldness of the Labrador Current that a contrast of 22° F. has been observed between stem and stern of an ice patrol ship lying across the boundary

between the Gulf Stream and Labrador Current there (16).

The investigation of the part played by the Gulf Stream in the climate of the eastern United States, what effects, if any, its variations have on the seasonal character of the weather, and whether such effects can be anticipated owing to the progressive movement of temperature departures in the Gulf Stream, may well begin with the surface temperatures of the Gulf Stream in the Straits of Florida. The varying strength of the current there should then be determined, in order to obtain from the volume of water and the temperature an approximation to the thermal cargo of the Gulf Stream at its source. The investigation should next take up the temperatures of the surface waters of the Gulf of Mexico and Caribbean Sea, and those of the Gulf Stream and other surface waters in the western Atlantic from the Grand Banks southward. Aside from preliminary general studies of the effect of the Gulf Stream or parts of the Atlantic Ocean on the condition of the overlying air and the climate of neighboring lands, an investigation of the part that Gulf Stream variations may take in seasonal weather must necessarily await the growth and adequate summarization of a reliable body of sea surface temperature data. However, even a few years of thermograph data may, as a basis for judging the accuracy of the bucket samplings, make possible the use of the bucket data for scientific purposes. Since these data extend nearly a century into the past, no effort should be spared to determine their limits of reliability for different parts of the ocean through the several seasons.

It appears, therefore, that a series of papers, such as the following nine, should be prepared to cover this general project:

I. Gulf Stream daily thermograms across the Straits of Florida.

II. Weekly succession of temperatures in the Straits of Florida, from thermograms, 1928-1930.

III. Thermal cargoes of the Gulf Stream through the Straits of Florida.

IV. Gulf Stream surface temperatures across the Straits of Florida—car-ferry series, 1917-1921 and 1928-1930.

V. Methods of mapping and summarizing ocean surface temperature data, with special reference to the Straits of Florida.

VI. Gulf Stream, West Indian, and other southwestern North Atlantic sea surface temperatures from the earliest records to the present time.

VII. Flooding rains in the eastern United States and their relation to evaporation from the Caribbean Sea, Gulf of Mexico, Gulf Stream, and tropical North Atlantic, as indicated by their surface temperatures.

VIII. The Gulf Stream during and prior to certain abnormal seasons in the eastern United States.

IX. Can the known or anticipated thermal cargoes of the Gulf Stream be used in forecasting the weather of a fortnight, month, season, or year in the eastern United States?

The first two papers in this list will appear in early issues of this Review. Numbers III, IV, and V have been given considerable study by the writer, and should appear within two or three years. Paper VI will represent a major job of compiling; it is now in progress for the region south of latitude 30° as a by-product of the revision of the West Indian portion of the North Atlantic Pilot Charts by the United States Weather Bureau. The relation of flooding rains in the eastern United States to the surface temperatures of the tropical waters on the south and southeast (VII) is an enticing subject, a sam-

pling of which by the writer is suggestive of interesting results. Papers VIII and IX, the capstones of the investigation, can not be prepared till the sea temperature compilations are done.

Obviously, the writer claims no monopoly on this subject. And he acknowledges his especial debt to the United States Weather Bureau for much of the progress already made. The chief, Prof. C. F. Marvin, has very cordially cooperated in many ways, and Mr. F. G. Tingley, in charge of the Marine Division, has been practically a partner in the investigation. There is enough in this general question of the effect of the Gulf Stream on the seasonal weather of the eastern United States to engage a number of capable investigators and assistants for several years. The rate of progress will depend on how many people become interested.

LITERATURE CITED

1. COYECQUE, M. and WEHRLÉ, PH.
1925. Hatteras Depressions. *Monthly Weather Review*, 53:26-27.
2. GREELEY, A. W.
1888. *American Weather*. New York, p. 104.
3. SANDSTRÖM, J. W.
1918. The Hydrodynamics of Canadian Atlantic waters. Canadian Fisheries Expedition, 1914-15. Ottawa. See pp. 230-231, 257-263, figs. 43-45.
4. JACOBSEN, J. P.
1929. Contribution to the hydrography of the North Atlantic. The "Dana" expedition 1921-22. Copenhagen. 98 p., 25 tables, 63 figs. Bibliog. Ref. to figs. 53-56.
5. WÜST, GEORG.
1924. Florida- und Antillenstrom, eine hydrodynamische Untersuchung. Veröff. Inst. für Meereskunde an der Universität Berlin, Neue Folge, A. Geogr. naturw. Heft 12. 48 p., 6 figs., 1 pl., bibliog. [Wüst brings together the observations by Bartlett, Pillsbury, and Bigelow.]
6. SMITH, EDWARD H.
1923. International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1922. U. S. Coast Guard Bull. No. 10, pp. 93-97.
7. SCHOTT, GERHARD.
1926. *Geographie des Atlantischen Ozeans*, 2d edition, p. 195.
8. PILLSBURY, JOHN E.
1891. The Gulf Stream. Methods of investigation and results of research. Report of the Supt. of the U. S. Coast and Geodetic Survey, year ending June, 1890, pp. 461-620. Popular summary in *Nat. Geogr. Mag.* 23:767, fig.
9. BIGELOW, HENRY B.
1917. Explorations of the United States Coast and Geodetic Survey steamer *Bache* in the western Atlantic January-March, 1914, under the direction of the United States Bureau of Fisheries. *Oceanography*. App. V. to the report of the U. S. Comr. of Fisheries for 1915.
10. IDRAC, P.
1929. Sur quelques singularités du Gulf-Stream. *Comptes Rendus (Paris)*, Acad. Sci., 188:644-646, figs. Transl. in *Mo. Weather Rev.* 57:206.
11. MARMER, H. A.
1929. The Gulf Stream and its Problems. *Geogr. Rev.* 19:457-478, 6 figs.
12. WÜST, GEORG.
1930. Der Golfstrom. *Zeitschr. d. Gesellschaft für Erdkunde zu Berlin*. 1930, Nr. 1-2:42-57, 7 figs.
13. BROOKS, CHARLES F., and MILLER, HAZEL V.
1929. Gulf Stream Temperatures in the Straits of Florida. *Bull. Am. Met'l. Soc.* 10:107-110.
14. BROOKS, CHARLES F.
1918. Ocean Temperatures in Long-Range Forecasting. *Mo. Weather Rev.* 46:510-512.
15. BROOKS, CHARLES F.
1926. Observing Water-Surface Temperatures at Sea. *Mo. Weather Rev.* 54:241-254 (including discussion), see especially p. 249-250.
16. WARD, R. DEC.
1924. A Cruise with the International Ice Patrol, *Geogr. Rev.*, 14:50-56, illus., Ref. p. 54. Cf. also *Mo. Weather Rev.* 52:71-78. Ref. p. 76, where temperature contrasts are mentioned.